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Transmission characteristic of fiber optic temperature sensor with chalcogenide glass sensing element

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The promising character of the use of the *As-Se*-chalcogenide glasses as the fiber-optic temperature sensors *(as sensing material for FOTS)* having optimal matching with spectral characteristics of the radiation source and receiver has been shown. The method of calculating the transmission characteristic of the fiber-optic temperature sensors has been elaborated. The calculation was carried out for the double-channel optical scheme with a (*sensing element*) in a form of a ~0.6 mm thick $As_{45}Se_{55}$ plate. In accordance with our calculations, the *As-Se* glasses can be used as the optimized sensitive elements for fiber-optic temperature sensors with input signal variation about 6 μA per 1 degree.

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1. Introduction

Information about the value of electric signal from the fiber optical temperature sensor (FOTS), the structural schematic diagram and the modern element base choice are important when developing FOTSs intended to measure temperature at a sufficient distance ($L > 1$ km) from the detecting unit in the areas harmful for human health (i.e. under radiation, high intensity electromagnetic fields, explosion hazard etc.) providing necessary accuracy and resistance (*noise immunity*) of measurement. These problems were studied in a number of papers [1-3].

The authors of Ref. [4] note, that the optical absorption spectra of semiconductor change with temperature that allows a fiber-optic temperature sensor to be built based on the semiconductor optical absorption phenomenon being capable of measuring temperature by detecting the optical transmittance permeating a semiconductor chip. The authors claim that this sensor system is simple by its structure, reliable in performance and suitable for measuring the ambient temperature. Because the system errors caused by different disturbances of the transmission fiber and characteristic excursion of the optoelectronic devices are difficult to be eliminated, therefore the accuracy of this sensor is low.

In Ref. [4], a new dual-wavelength compensation system has also been proposed. There are two sources of light emission: the operating and the reference light beams. Emission of these sources has different spectral characteristics, i.e. the maximum spectral intensity corresponds to a wavelength of 0.880 μm for the operating beam and 0.950 μm for the reference one. The disadvantage of the proposed device is the difficulty of its optical system matching and adjustment and the complexity of the procedures of processing the information signal from the optical sensor.

At present, the LEDs with different fixed operating wavelength λ_s are available commercially. Their spectral bandwidth is quite narrow; they possess high output beam luminous flux time stability and long operating time. At the same time, there is a wide range of high-sensitivity low-noise optical radiation receivers, the maximum spectral characteristics of which may correspond to different wavelengths λ_r. Moreover, it is easy to find a 'LED – receiver' pair for which $\lambda_s \approx \lambda_r \approx \lambda_0$. In such circumstances, they reach the maximum sensitivity of the waveguide optical systems when measuring the physical quantities. In particular, the M808D50-3-1230 LED [5] and the OPT101 photodiode (λ_0 = 0.808 μm) lasers satisfy all of the above conditions.

The LED emission spectrum and the photodiode spectral sensitivity must lie in the region of the fundamental absorption edge of the sensing element material. It would be quite reasonable, if in the measuring system the temperature sensor itself changes its optical informational parameter with the maximal range at the same wavelength λ_0. For the crystalline materials typical for optoelectronics, it is extremely difficult to make such selection. Much easier this task is solved in the case of the chalcogenide vitreous semiconductor (ChVS) due to the possibility of wide variation of their chemical composition and appropriate physical properties [6]. Present design is aimed at developing the method of calculating the transmission characteristic, evaluating the value of light signal attenuation in the FOTS fiber optical route defined by the emission source and sensor choice. This allows the optical matching in the LED-sensor-photodiode system to be optimized.

2. Methods

The *As-Se* ChVS were chosen as the materials for the temperature sensors due to the fact that by the change in composition we can provide optimal coordination of the sensitive element with the LED and photodiode, which are available on market.

The samples were synthesized using the basic components of high purity elemental substances by applying chemical methods in the pretreated quartz ampoules (20 mm in diameter). The ratio of the initial arsenic and selenium components in the mixture of components complied with the chemical composition of glass with 25, 45 and 65 at % of As (at higher arsenic concentrations we failed to obtain optically homogeneous glass).

As_xSe_{100-x}(x=25,45 and 65) glasses were prepared by vacuum co-melting of the relevant mixture of high-purity As and Se elemental substances in quartz ampoules (20mm in diameter). The ampoules were heated with the rate of 2-3 K/min and kept at homogenization temperature of the melts (600-700K) for 24 hours. The melts were periodically stirred. Cooling of melts was carried out into cold water.

The sensitive element were produced from the synthesized glasses by a hot pressing technology to form the d = 0.6 mm thick plates according to the procedure described by us earlier [7].

The absorption spectrum of the sensors and their temperature dependence were studied using a SF101 spectrophotometer according to the technique described in [8].

3. System design

3.1. Sensor system

In order to eliminate the effect of the emission source instability on the measuring accuracy, the double-channel single ray FOTS scheme was suggested (see fig. 1) using the optical Y-splitter that splits in half the ray coming from the emission source 1 producing, thus, the operating and the reference channels. Then the optical signals are transformed into the electric ones by means of the receivers 5, 6 and are split by the signal splitter 7. The resulting signal is transmitted to the detection unit.

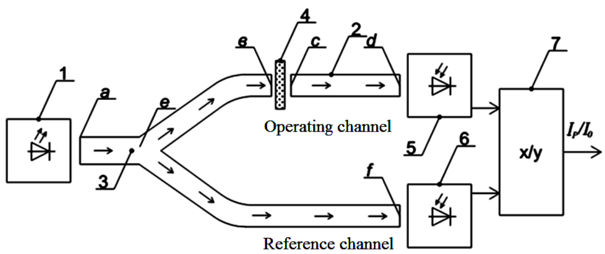

Fig. 1. Combined FOTS structural diagram 1 – emission source (LED); 2 – multi-mode optical fiber; 3 – optical fiber Y-splitter; 4 – chalcogenide glass plate; 5, 6 – emission detectors (photodiodes); 7 – electric signal splitter (I_0/I_p)

3.2. Emission source

The M808D50-3-1230 laser LED [5] satisfies the optical matching condition for our sensor system. The spectral characteristic of the emission power is presented in Fig. 2. Its maximum corresponds to the λ_0 = 0.808 µm, at which the maximum sensitivity of the *As-Se* plate is observed. A positive feature of this LED is also a quite narrow spectral width of radiation, which is less than a half of the maximum range (8 nm). Moreover, the narrow light beam source (0.25 mm diameter) simplifies adjustment of the system and makes it possible to input a large part of LED emission power into the optical fiber of the device.

Selected LED consumes very low power due to the following parameters:

– optimal LED operating current level I_{np} =100 mA;

– integral emission power at I_F=100 mA is not less than 50 mW;

– optimal operating current I_o = 100 mA;

– input resistance R = 4.0 Ohm; operating temperature range T = 233 … 358 K.

3.3. Emission detector

The spectral characteristics of a photodiode should be matched with the LED working wavelength and with the sensor. Furthermore, we have also taken into account the design features of its coupling with the optical fiber. The OPT101 photodiode satisfies these requirements. Its spectral sensitivity characteristic is shown in Fig. 3. Apparently, the sensitivity range of this photodiode is much wider as compared to that of the LED emissivity, but the working length of our device radiation λ_0 = 0.808 µm falls into the region of the maximum spectral sensitivity of photodiode.

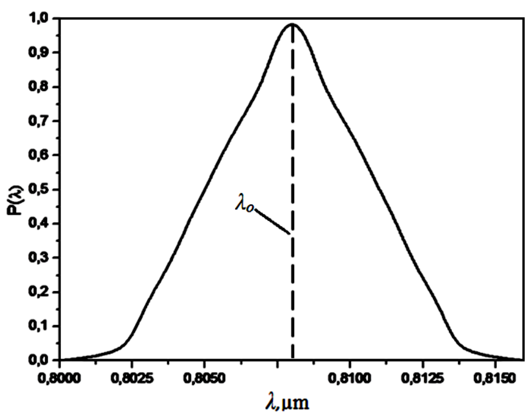

Fig. 2. Spectral dependence of the M808D50-3-1230 laser LED emission power [5]

The OPT101 photodiodes possess good electrical characteristics. They operate within a wide range of operating voltages from 3 to 36 V and have a current integral sensitivity (S_{in}) not less than 0.55 A/W. At the same time their geometric parameters plate dimensions:

2.9×2.9 mm^2 and face angle of view $2\beta = 36\,^{o}$) provide optimal matching between the detector and the optical fiber. One may note also a high speed of the OPT101 photodiodes, i.e. the maximum time constant at switching on/off is $t = 0.005$ μs.

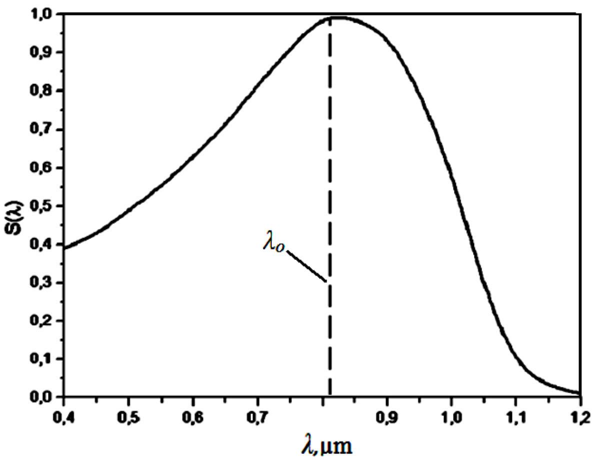

Fig. 3. OPT101 photodiode spectral sensitivity characteristic [9].

3.4. Optical fiber

For the working and reference channels we selected a multi-mode boron-doped quartz optical fiber FinMark PS001MM PVC [10]. The refractive index of its core $n = 1.553$ at the $\lambda = 0.81$ μm. These fibers have losses at the level of 2.7…3.0 dB/km and can work within the temperature interval from 213 to 443 K.

4. Results and discussion

4.1. Spectral investigations

The results of the spectral studies of absorption edge for the As_xSe_{100-x} glasses are summarized in Fig. 4.

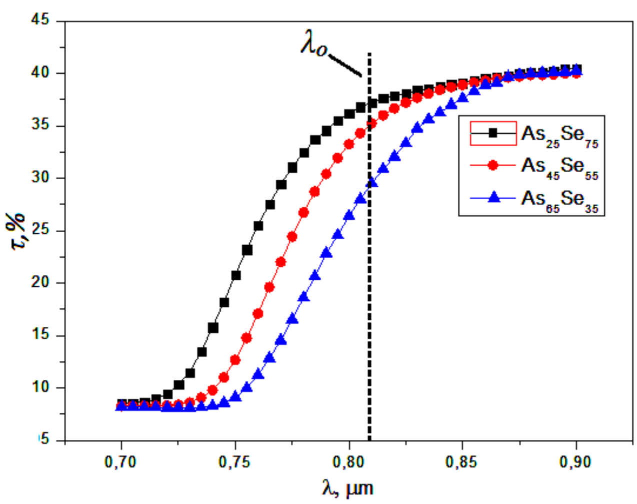

Fig. 4. Summarized spectral studies of the transmittance edge for the As_xSe_{100-x} glasses

The operational principle of FOTS is based on the shift of the fundamental optical transmission edge of the ChVS plate with the temperature variation. As is known, with the temperature increase the shift of the absorption edge for the *As-Se* glasses towards the larger wavelengths is observed. Therefore, the upper limit of the interval linearity of the dependence $\tau = \tau\ (x)$ determines the optimal sensor operating wavelength. As follows from Fig. 4, the $As_{45}Se_{55}$ sensor complies with the condition of the spectral optimization of the main optical elements of the temperature sensor.

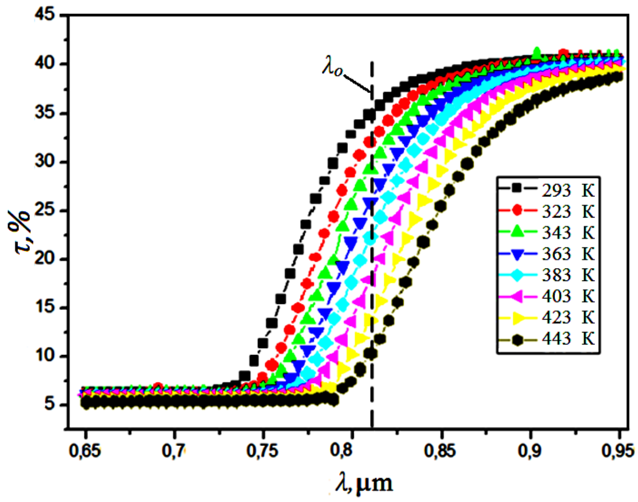

Fig. 5. Spectral dependence of the 0.6 mm thick $As_{45}Se_{55}$ -plate absorption for different temperatures

To check the above conclusion, we have studied experimentally the processes of the transmittance edge shift for the $As_{45}Se_{55}$ plates at their temperature variation. The results of these studies are shown in Fig. 5. Accordingly, the sensor transmission at $\lambda_0 = 0{,}808$ μm decreases monotonously from $\tau = 35\%$ to $\tau = 10\%$ at the temperature increase from 393 K to 443 K. It should be also noted that, in mathematical sense, the above variation law is very close to linear one and is described fairly well by a simple relation $\Delta\tau = k\cdot(T - 393)$, where k is the sensor sensitivity and T is its temperature. From the data displayed in fig. 6, we have found that $k = 0.12\%$.

The $As_{45}Se_{55}$ ChVS softening temperature is $T_g > 450^{o}$K [11] and specifies the upper limit of the sensor operating temperature range. However, our studies show the possibility of a stable operation of this device for dozens of minutes at the sensor temperature by 20 – 30 K below the flash point.

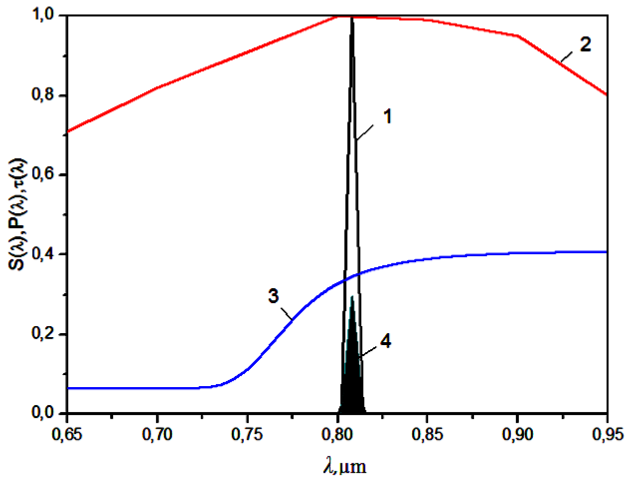

Fig. 6. Spectral dependence (S (λ) P (λ) τ (λ)) of the FOTS optical scheme elements and their matching: 1 – emission source; 2 – emission detector; 3 – thermo-sensitive element (at room temperature); 4 – resulting flux onto detector

4.2. Calculation of light energy entering the FOTS emission detector area

The values of the electric signals at the photodiode output for both the operating and the reference channels depend directly on the light flux intensity. Let us estimate this light energy value. Let the LED current be I_{op} = 50 mA. The integral emission power will be $P_{int} = 40{\cdot}10^{-3}$ W. Since the diameters of the emitting LED area and the optical fiber core are different, only a small part of the light energy P_{in} will enter the optical fiber that may be calculated as:

$$P_{in} = P_{\text{int}} \cdot \frac{S_f}{S_d} \tag{1}$$

where S_f, S_d are the emitting LED area and the optical fiber core area, respectively. Taking into account the technical parameters of the above elements, we obtain after calculating: $P_{in} = 8{\cdot}10^{-3}$ W.

P_{in} value is small as compared with P_{int}. Therefore, to increase the value of the light flux entering the optical fiber, we have developed the optical connectors comprising focons. This allowed the efficiency of the light input into the optical fiber to be increased 4 times, and $P_{in2} = 32{\cdot}10^{-3}$ W.

The P_{in} values obtained by us will enable long ($L \sim 10^3$ m) optical communication lines between the light source and light detector to be constructed.

Let us estimate the light ray attenuation due to the Fresnel reflection at the optical media boundaries on its way from LED to photodiode. At normal ray incidence onto the two isotropic media interface, the transmittance will be determined by the following formula:

$$\tau = 1 - \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2, \tag{2}$$

where n_1 and n_2 are the refractive indexes of the adjacent media.

At the operating wavelength of λ_0 = 0,808 μm the plate material refractive index is n = 2,774 [12].

In Fig. 1, these boundaries are denoted by *a, b, c, d* for the operating channel and by *f* for the reference one. Let us assume that at the point (*e*) of the Y-splitter the light ray intensity is divided in half (i.e. τ_e = 0.5).

The resulting transmittance coefficient of the above optical system will be determined as the product of the coefficients for the adjacent media. Thus, the operating channel transmittance will be:

$$\tau_o = \tau_a \cdot \tau_e \cdot \tau_b \cdot \tau_c \cdot \tau_d \tag{3}$$

Similarly, the reference channel transmittance will be:

$$\tau_r = \tau_a \cdot \tau_e \cdot \tau_f \tag{4}$$

Taking into account the above refractive index values for contacting media, we find that τ_O = 25% and τ_R = 45,5%.

The powers of the light fluxes entering the photodiodes of the reference and operating channels will be, respectively:

$$P_r = P_{in2}{\cdot}\tau_r = 32{\cdot}10^{-3}{\cdot}0.455 = 14.56 \text{ mW}$$

$$P_o = P_{in2}{\cdot}\tau_o = 32{\cdot}10^{-3}{\cdot}0.250 = 8.00 \text{ mW}$$

4.3. Photodiode current calculation

As was mentioned above, the photodiodes were used as the emission detectors in the operating and reference channels to transform the optical signal into the electric. When performing the analytical calculations of the photodiode currents, one has to know not only the values of these fluxes, but also the efficiency of the use of the LED emission by the photodiode related to different spectral distributions of its emissivity and the photodiode sensitivity (figs. 2, 3). The photodiode current in our case may be estimated by the following formula:

$$I_{PD} = \tau_{o,r} \cdot \int_{\lambda_1}^{\lambda_2} S^a(\lambda) \cdot P_\lambda^a(\lambda) \cdot \tau(\lambda) d\lambda \tag{5}$$

where: $S^a(\lambda)$ is the spectral distribution of the photodiode sensitivity in the absolute units [A/W];

$P_\lambda^a(\lambda)$ is the dependence of the spectral density of the emission diode in the absolute units [W/m];

$\tau_{o,r}$ is the transmittance of the reference or, respectively, operation FOTS channels. We shall assume these quantities be constant;

$\tau(\lambda)$ is the spectral dependence of the sensor transmittance at given temperature;

$(\lambda_1 - \lambda_2)$ is the photodiode sensitivity spectral range.

Finding the photodiode current using formula (5) is complicated by the fact that, as a rule, the emission source and the detector specifications provide the spectral distributions of the emissivity and relative sensitivity of the photodiode in the relative, not absolute, units $P^r(\lambda)$, $S^r(\lambda)$ are determined as:

$$P^r(\lambda) = \frac{P^a(\lambda)}{P_m^a(\lambda_m)} \quad (6)$$

$$S^r(\lambda) = \frac{S^a(\lambda)}{S_m^a(\lambda_m)} \quad (7)$$

where $P_m^a(\lambda_m)$, $S_m^a(\lambda_m)$ are the maximal values of the sensitivity *S* and emissivity *P* of the photodiode and LED, respectively, at the λ_m wavelength expressed in the absolute units.

To find I_{PD} from expression (5), one has to know $P^a(\lambda)$, $S^a(\lambda)$. Let us find these quantities from (6) and (7).

$$S^a(\lambda) = S^r(\lambda) \cdot S_m^a(\lambda_m) \quad (8)$$

$$P^a(\lambda) = P^r(\lambda) \cdot P_m^a(\lambda_m) \quad (9)$$

Substituting (8) and (9) into (5), we obtain:

$$I_{PD} = \tau_{o,r} \cdot S_m^a(\lambda_m) \cdot P_m^a(\lambda_m) \cdot \int_{\lambda_1}^{\lambda_2} S^r(\lambda) \cdot P^r(\lambda) \cdot \tau(\lambda) d\lambda \quad (10)$$

The values of $P_m^a(\lambda_m)$, $S_m^a(\lambda_m)$ could also not be found in the reference books. More often, one may find the integral sensitivity values for the photodiode and the LED emissivity [13].

On the other hand, the integral values, according to ref. [13], could be presented in a form:

$$S_{\text{int}} = \int_{\lambda_1}^{\lambda_2} S^a(\lambda) d\lambda \Big/ \int_0^\infty \varepsilon(\lambda) d\lambda \quad (11)$$

where $\varepsilon(\lambda)$ is the spectral radiation density of the reference source, for which the photocopier was certified for the selected photodiode, taking into account the spectral sensitivity area, it is a black body model (absolutely black body) at a temperature $T = 2850$ K.

Substituting expression (8) into (11) instead of $S^a(\lambda)$:

$$S_{\text{int}} = \int_{\lambda_1}^{\lambda_2} S^r(\lambda) \cdot S_m^a(\lambda_m) d\lambda = S_m^a(\lambda_m) \cdot \int_{\lambda_1}^{\lambda_2} S^r(\lambda) d\lambda, \quad (12)$$

From (12), we shall find the value of $S_m^a(\lambda_m)$:

$$S_m^a(\lambda_m) = \frac{S_{\text{int}}}{\int_{\lambda_1}^{\lambda_2} S^r(\lambda) d\lambda} \quad (13)$$

Similarly:

$$P_{\text{int}} = \int_{\lambda_1}^{\lambda_2} P^a(\lambda) d\lambda = \int_{\lambda_1}^{\lambda_2} P^r(\lambda) \cdot P_m^a(\lambda_m) d\lambda = P_m^a(\lambda_m) \cdot \int_{\lambda_1}^{\lambda_2} P^r(\lambda) d\lambda, \quad (14)$$

Hence:

$$P_m^a(\lambda_m) = \frac{P_{\text{int}}}{\int_{\lambda_1}^{\lambda_2} P^r(\lambda) d\lambda} \quad (15)$$

Substituting (13) and (15) into (5), we obtain an expression for I_{PD} for both the reference $I_{PD\ r}$ and the operating $I_{PD\ o}$ channels:

$$I_{PDr} = \tau_r \cdot S_{\text{int}} \cdot P_{\text{int}} \cdot \frac{\int_{\lambda_1}^{\lambda_2} S^r(\lambda) \cdot P^r(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} P^r(\lambda) d\lambda} \quad (16)$$

$$I_{PDo} = \tau_o \cdot S_{\text{int}} \cdot P_{\text{int}} \cdot \frac{\int_{\lambda_1}^{\lambda_2} S^r(\lambda) \cdot P^r(\lambda) \cdot \tau(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} P^r(\lambda) d\lambda} \quad (17)$$

Obviously, when calculating $I_{PD\ r}$ $I_{PD\ o}$ for these channels, we shall use the calculated light flux power $P_{in2} = 32 \cdot 10^{-3}$ W instead of P_{int}.

The photodiode currents were calculated for both channels by a numerical integration method using the applied software, in particular, the MathCad program that allows the output current values to be obtained operatively when modeling different variations of optical schemes and elements used in them.

Choosing the optic coupler elements provides high optical matching with the thermo-sensitive element material characteristics, as shown in Fig. 6.

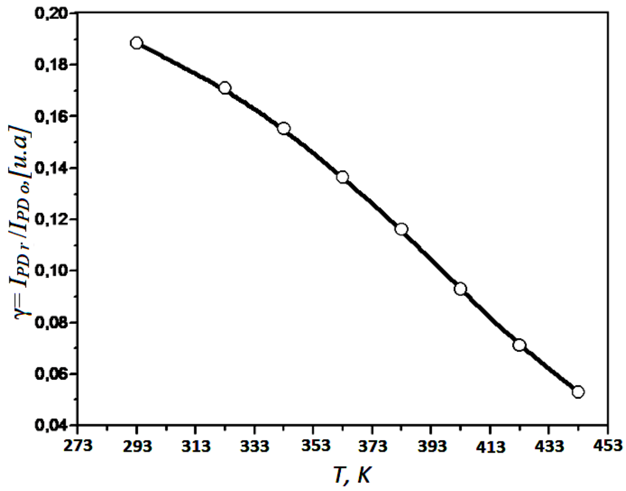

Fig. 7. FOTS transmission characteristic

The reference channel photodiode current calculated by (16) is $I_{PD\ r}$ = 6.7 mA. The operating channel current varies from 1.28 to 0.36 mA at the thermo-sensitive element temperature change from 293 to 443 K. As a result of these currents change, we obtain a signal proportional to the temperature change that further is supplied to the microcontroller for processing. The FOTS transmission characteristic for the proposed optical scheme is presented in Fig. 7.

5. Conclusions

The method of calculating the double-channel optical scheme of the optical fiber temperature sensors with the sensitive element in a form of a thin plate made of the chalcogenide vitreous semiconductor has been proven theoretically. Calculations of the transmission characteristic of such sensors demonstrate a promising character of the use of the *As-Se* chalcogenide glasses as the fiber-optical temperature sensors ensuring high level of matching with spectral characteristics of the radiation source, receiver and sensor. The transmittance spectrum studies have shown that for the 0.808 μm optical path wavelength the chalcogenide $As_{45}Se_{55}$ glass-based sensors have the optimal parameters. The transmittance characteristic of the optical fiber temperature sensor with the above sensitive element (0.6 mm thick plate) demonstrates almost linear dependence of the radiation receiver current on the sensor temperature with at least 6 μA per 1 degree sensitivity.

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